Pervasive and Mobile Computing ▮ (▮▮▮▮) ▮▮▮–▮▮▮

Contents lists available at ScienceDirect

Pervasive and Mobile Computing

journal homepage: www.elsevier.com/locate/pmc

The immersive effect of adaptive architecture

Holger Schnädelbach [a,*], Petr Slovák [b], Geraldine Fitzpatrick [b], Nils Jäger [a]

[a] *Mixed Reality Lab, School of Computer Science, University of Nottingham, United Kingdom*

[b] *Human Computer Interaction Group, Institute for Design & Assessment of Technology, Vienna University of Technology, Austria*

ARTICLE INFO

Article history:
Received 8 April 2014
Received in revised form 5 September 2014
Accepted 13 November 2014
Available online xxxx

Keywords:
Pervasive computing
Adaptive architecture
Respiration
Immersion
Experience

ABSTRACT

This paper explores the role of immersion in the generation of specific interactive effects, within the context of the emerging research field of Adaptive Architecture. Drawing on an existing biofeedback-driven prototype that links a person's respiration to the form of their environment, the study presented here compared an immersive condition with a non-immersive condition to capture differences in participant experiences. The immersive condition afforded the majority of participants a relaxed, embodied experience, whereas the non-immersive condition left people unconnected. The study did not surface statistically significant differences in participants' physiological responses between the two conditions. The study findings contribute to the understanding of our relationship with adaptive environments, underpinned by pervasive computing technologies, as they emerge in the Arts and Architecture.

© 2014 Elsevier B.V. All rights reserved.

1. Introduction

Architecture is typically considered to be mostly static, even though all buildings can be adapted by people to some extent, as Brand illustrates [1]. There is also a type of Architecture that is specifically designed to be adaptive to its environment and its inhabitants, ranging from traditional Japanese dwellings to modern eco homes. This *Adaptive Architecture* is finding increased interest because of the new possibilities that pervasive computing technologies embedded in buildings present and it is pursued under various guises [2]. Pervasive computing in this context allows buildings to be driven by inhabitation, drawing on various types of personal data whether this is location information, information about activity or social networking data to mention a few examples [3,4]. Related to this there is a growing interest in making the resulting spaces smart, recognising and supporting activities in whole host of application areas [5].

In one specific area of the larger research endeavour, a number of adaptive prototypes have started to explore reactivity around one specific type of personal data: physiological data. This is particularly interesting, as physiological data often remains hidden even to ourselves, and it is frequently perceived as private. Reacting to this, experimental projects in the Arts and Architecture play with our expectations about physiological data by exposing it to various degrees to the individual and to others. For example, 'Breathe' explores the environmental playback of respiration data to another person [6], while 'Drawing Breath' allowed for the graphical exploration of respiration [7]. More indirectly, Khan's Open Columns prototype employed CO_2 levels, as emitted by inhabitants, to influence group behaviour [8]. ExoBuilding, which we have had access to for the experimental work presented here, explores the link between an inhabitant's respiration and the size and form of its building envelope [9] (a description of ExoBuilding is included further below). As the above examples demonstrate, research

* Corresponding author. Tel.: +44 115 9514094.
E-mail address: holger.schnadelbach@nottingham.ac.uk (H. Schnädelbach).

http://dx.doi.org/10.1016/j.pmcj.2014.11.006
1574-1192/© 2014 Elsevier B.V. All rights reserved.

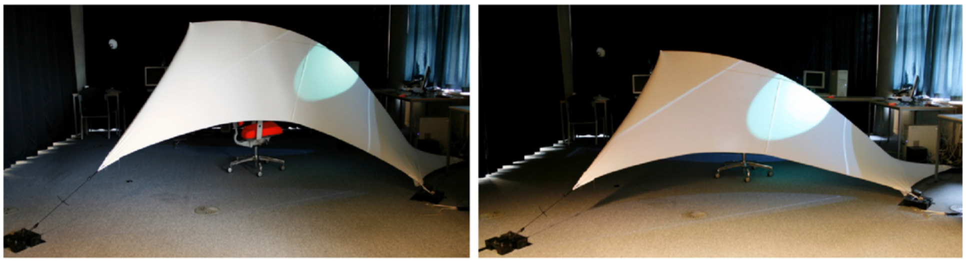

Fig. 1. ExoBuilding extended and contracted.

Fig. 2. View of a person experiencing ExoBuilding.

into Architecture is concerned not just with buildings but it is a much wider endeavour seeking to understand our relationship with the environment around us and this is expressed through the adoption of a wide variety of approaches [10–13].

Although we now have a very good understanding of how to technically drive adaptations and how to create adaptive environments in the sense that they were described above, we are still lacking a good understanding of how inhabitants experience those and their potential effects. There are arguably a number of reasons for this lack of understanding. The opportunity to study such environments has not existed for that long, especially when one looks at Adaptive Architecture driven by personal data. The type of work that is listed above as background and which could be studied, is typically created in a context where systematic study is not the norm. Experimental Adaptive Architecture is frequently created to explore issues in the tradition of architectural and art critique; the work around Sonic Cradle is one key exception [14]. Where adaptive architecture has been studied in detail, for example in a number of living labs [4,15], it has been of prototypes that are not responsive in the same sense as the most experimental work. In particular, to the best of our knowledge, the role of biofeedback remains underexplored through this approach.

Overall, the work presented in this paper is one output of this wider research programme into our relationship with adaptive environments, whether they emerge from work in the Arts or from Architecture. More specifically, through the study presented here, we seek to address the role of immersion within adaptive environments in the generation of certain inhabitant experiences: Given a specific type of interactivity (as for example highlighted in the examples presented above), what differences can we find between experiencing this interactivity from within and from outside? This seems particularly important as such immersive, encompassing experience is one of the crucial characteristics of Adaptive Architecture specifically and Pervasive Computing more generally, but has been under-researched so far. To start addressing this question, we draw on an existing prototype called ExoBuilding. As outlined in more detail below, ExoBuilding changes its shape in real time, being directly driven by users physiological data, but also allows the users to experience such bio-feedback in both immersive and non-immersive ways.

2. Exobuilding

For this study, we used the previously developed adaptive environment ExoBuilding. The following is a succinct introduction of this prototype with a full description available in [9]. ExoBuilding is a tent-like fabric structure mounted from the ceiling. Via two servomotors, its central flexible spine can be pulled up and released, allowing for changes in form and size. A data projector is used to project a circular graphic on its outside, helping to emphasise its physical movement in a darkened room, see Fig. 1. Respiration data is acquired from sensors worn by a single inhabitant sitting on a reclined chair, see Fig. 2. Respiration drives the extent of the room-sized structure made from stretchable fabric, so that the volume increases when the person inhales and so that it decreases when the person exhales.

ExoBuilding technically immerses its inhabitant by shutting out the remainder of the physical space visually and by the way its movement is driven by its occupant.

Please cite this article in press as: H. Schnädelbach, et al., The immersive effect of adaptive architecture, Pervasive and Mobile Computing (2014), http://dx.doi.org/10.1016/j.pmcj.2014.11.006

ExoBuilding was originally developed to study the use of personal data in the field of Adaptive Architecture, as described in the introduction. It focuses on the most personal of data: physiological data. Our aim was to investigate how we might live with such data being available in the built environment, where this is technically very much possible and is being suggested by technologists and architects alike. ExoBuilding itself is then also a broader platform than what is necessary for the work presented here. We have already explored links between EDA, heart rate and skin temperature to environment movement, sound, image projections and light effects with this platform and continue to seek technical extensions and new application areas.

In a previously reported study [16], the immersive biofeedback enabled through ExoBuilding triggered behavioural changes and changes in participants' physiology, when compared to a regular movement condition and the static prototype (control). In the control condition participants occupied the 'un-actuated' prototype, with it not moving at all. In a regular condition, the prototype moved at the regular pace of six cycles per minute, which is close to breathing patterns trained for in respiration training [17]. In the biofeedback condition, the prototype followed participants as already described above. Only in the biofeedback condition did participants change their respiratory behaviour, lowering their respiration rate, increasing their respiration amplitude and exhibiting regular respiration patterns. In addition, a sizeable proportion of study participants also reported how they found the biofeedback condition relaxing which was often framed by discussions of the link between the prototype and their bodies.

As all conditions compared in the original ExoBuilding study involved participants being immersed inside it, it is unclear whether the strong effects generated by the bio-feedback condition were caused by the interactivity alone or by immersively experiencing that interactivity.

3. Exobuilding to study immersive effect

To study the role of immersion in people's experience of ExoBuilding, as exemplar adaptive environment, we designed a focused study comparing an immersive condition with a non-immersive condition.

3.1. Study design

The immersive condition (1) involved the participants sitting inside ExoBuilding with their respiration mapped to the movement of the prototype (the interactivity being equivalent to the biofeedback condition in the original study). The non-immersive condition (2) involved participants sitting in the enclosed space that ExoBuilding is located within, facing ExoBuilding. Their respiration was linked to the movement of the prototype in the same fashion as for the immersive condition, the overall lighting, the light on the prototype fabric and all environmental conditions were kept constant, so that the only difference between the conditions was the participant's location.

We designed the study to explore the subjective experiences our participants had when immersed and when not being immersed and to allow for the comparison of potential differences in physiological data (within-subjects repeated measures design with participants experiencing each of the experimental conditions, lasting 10 min) should they appear. The order of the two conditions was counter-balanced, with half the participants starting with (1) and half with (2).

3.2. Participants

Participants were recruited by local advertisement. In pre-trial screening we excluded anyone with a heart condition, respiratory problems, panic disorders and claustrophobia, smokers, people consuming more than the UK recommended levels of alcohol, people with regular drug intake (prescription or otherwise) and those being treated or having been treated in the past for any psychological condition. There were 24 participants in total (19 male, 5 female). Their ages ranged from 18 to 63 years, with a median age of 24. They were informed of the study procedure and told that the study was to investigate the effect of a new technology on relaxation. They were also informed of their right to withdraw from participation at any time.

3.3. Study procedure

Participants were fitted with a Mindmedia Nexus-10 physiological data-monitoring device [18] collecting respiration data (RSP), the Electrocardiogram (ECG) and electrodermal activity (EDA) data. For a short period (∼3 min), participants then experienced their physiological data being mapped to ExoBuilding when sitting outside it. Participants were asked to experiment to see and understand the extent of the effects of their behaviour. This allowed participants to get used to this mapping and to explore its range, and was designed to minimise the chance of them experimenting with this at the start of the first condition. Participants were asked to complete a short questionnaire, as part of a cover story, about probing work related stress (not part of the analysis). They were then required to complete a to-do list for all activities they needed to do in the next two weeks, to get participants mildly stimulated.

Both experimental conditions were then framed by specific and identical instructions to concentrate on breathing. These in turn were *pragmatically* drawing on instructions given in mindfulness training [19], as such instructions are common and established there, avoiding us having to invent our own. We would like to emphasise that we did not specifically set out for people to become mindful or to measure mindfulness. For the untrained, a focus on respiration can be relatively difficult to achieve. ExoBuilding gives tangible feedback on respiratory behaviour (thus possibly helping unskilled people pay attention to their breathing). This is constant across the two conditions apart from immersion, and this focus on breathing therefore seemed ideal for surfacing the differences between our conditions.

Our instructions were: "Try to concentrate on your breathing, and nothing else. Bring attention to your breathing, how your belly moves up and down when you breathe in and out. If you find yourself thinking about something else, just note that this happened and bring your attention back to breathing. Even if this happens a hundred times over the next 10 min, your goal is always to just bring your attention back to the breathing".

Following the first experience with ExoBuilding (with either immersive or non-immersive coming first), participants were asked to return to the to-do list, adding activities that they had to do to complete the tasks that they previously listed. The aim was to get them out of states of relaxation that they might have gained through the experimental condition and minimise any carry-over effects between the conditions. Both experimental conditions were followed by a short questionnaire probing for the adherence to the instructions during the two experimental conditions. The final condition was followed by an in-depth semi-structured interview, probing participant's qualitative responses to the two conditions.

3.4. Expectations

Considering that the two conditions were interactionally the same, we expected that the immersive condition would provide a more 'powerful', engaging experience. The type of tangible and immediate feedback on respiratory behaviour engendered by ExoBuilding was expected to affect the subjective experience of the two conditions. We were therefore aiming to gather detailed feedback of any experiential differences between the conditions through the interviews. We also expected differences in support to our participants with regard to adhering to our respiration instructions, and anticipated that the immersive condition would make it 'easier' for participants to comply with our breathing instructions because of the embodied nature of the biofeedback through the immersive, enclosing nature of the prototype. These expectations were shaped by the previously mentioned study results of the prototype that had shown its potential to influence respiration patterns, and through this other physiological data streams, without providing participants with instructions [16].

In the study presented here, the instructions to concentrate on breathing were introduced, focusing on uncovering any effects that immersion might have. Those instructions did not aim at a change in physiological behaviour per se and were identical for the two conditions. As such our hypothesis was that levels of activation would be the same between conditions (EDA and HR). We also hypothesised that respiratory behaviour would be influenced by better levels of concentration on the breathing instructions enabled by the immersive condition, and therefore expected lower respiration rates (RSP-R) and better respiration heart rate coherence (RSP-HR-COH) there (see below for an explanation of the recorded measures).

3.5. Data collection and rationale

Semi-structured interviews aimed to uncover the experiential differences between the immersive and non-immersive conditions. A questionnaire was administered to probe how participants coped with our respiration instructions across the two conditions. Physiological data was collected to measure participants' physiological and behavioural responses to immersive and non-immersive biofeedback through ExoBuilding, should they arise.

3.5.1. Interviews—participant experiences

Semi-structured interviews were conducted with all 24 participants, following the completion of both conditions. These interviews began by probing the overall experience that people had, prompting participants to freely describe this, and for them to provide detail. This was followed by prompts for participants to compare the two conditions, to compare the before and after of each condition, and to reflect more generally beyond the core instructions to concentrate on breathing. Interviews were audio recorded. Using InqScribe, the interviews were first fully annotated while listening to them. This allowed us to identify pertinent parts, which were then fully transcribed. Responses were then grouped, from which a set of themes emerged. The groupings and themes were confirmed in data-sessions involving the two first authors and colleagues. Below we present (through basic themes) exemplary qualitative material to provide a direct insight into people's responses.

3.5.2. Questionnaires—coping with respiration instructions

A short questionnaire was administered following each of the conditions. Through three core statements, this probed for feedback on how participants coped with the particular instructions they were given: to concentrate on their breathing. The exact statements were: 'I found it hard to keep my attention focused on breathing.', 'I often had to consciously return to the breathing' and 'When my thoughts got carried away from breathing, I realised it quite quickly'. There were six additional statements (not of interest here) that aligned with the cover story of a study into work-related stress. Participants selected their answer on a 7-point Likert scale, ranging from 'Strongly Disagree' (1) to 'Strongly Agree' (7).

Please cite this article in press as: H. Schnädelbach, et al., The immersive effect of adaptive architecture, Pervasive and Mobile Computing (2014), http://dx.doi.org/10.1016/j.pmcj.2014.11.006

3.5.3. Physiological data—the physiological response to the two conditions

We briefly describe the collected physiological measures below, with a full description of the relevant measures available in [16]. *Electrodermal Activity (EDA)*: EDA was measured via two electrodes placed on separate fingers of the non-dominant hand. The study concentrated on the longer term tonic EDA (EDL) which tends to decrease in relaxed and increase in activated states [20]. The well-reported issues with EDL drift were deemed to be irrelevant for the short trial length. *Electrocardiogram (ECG)*: ECG was measured with electrodes attached to participants' torsos, from which *Heart Rate (HR)* was derived in beats per minute (bpm) as an index into physical activation. *Respiration (RSP)*: RSP was measured with a respiration belt fitted around the participants' abdomen, producing a trace for abdomen movement, from which *Respiration Rate (RSP-R)* (cycles per minute (cpm)) was derived. RSP-R rises with physical activity and falls to a personal base level at rest. RSP-R was included as an index into respiratory behaviour, with the instructions aiming at influencing respiration. *Relationship of respiration and cardiovascular measurements*: Heart rate increases during inhalation and decreases during exhalation in the frequency of the respiration cycle, resulting in heart rate variability (HRV). This relationship is captured as *respiration to heart rate coherence (RSP-HR-COH)*. A closer adherence to our respiration instructions should result in higher RSP-HR-COH. For each trial, 10 min of data was recorded, with the 'central' nine minutes used for analysis, avoiding any influences of the start and end of sessions. One participant's ECG signal was faulty, leaving only EDA and RSP-R for that participant.

4. Qualitative data: interviews

We now move on to outline the core results from this study—the exploration of the descriptions of the participants' experiences in the immersive versus the non-immersive condition. As we show below, the majority of our participants described markedly different experiences in the two conditions. We start with summarising the common topics a perceived in the immersive condition.

4.1. Inside—immersive

Fifteen of our participants stated explicitly that they experienced the immersive condition as more relaxing than the non-immersive condition. When describing this, they compared the feeling to being extremely relaxed, calm, similar to just before falling asleep; describing how the immersive condition created an experience of safe, cosy places; places where one can just let go and relax. For example:

P09: Inside the tent it was a bit like daydreaming, I almost fell asleep at some point. It was very strange because you get so relaxed …
P13: The way mind wondered was more like when trying to go to sleep but am unable to... but it was much more relaxed, more freeflowing.
P17: Sort of like when you're in bed at night and you're tucked in quite well, sort of that feeling, same kind of relaxation.
P23: When I was inside the tent that was totally relaxing, absolutely relaxing. A different feeling altogether, something very new to me.

Many participants also described the experience as peaceful, related to being in their own space, detached from the world. This brought to focus just what is inside the tent (i.e., either the tent, or their thoughts).

P24: More private, [a] little safe cubbyhole. You can't see anything but the tent, blocks everything else out.
P03: More surrounded like in a bubble, so that's why inside I was more focused on … my list and things I need to do. Because I think I was in my little surrounding where I was just focused on exactly what was going through my mind.
P09: When I was in the tent, I felt like in childhood, like proper safe you know, not worried about anything at all. That was strange; but that's why I could get relaxed so much.
P25: You're just closed off, as far as you are aware the only world is inside there.

In particular, breathing itself felt very natural, where people were able to keep it up without conscious effort. People reported that they were able to keep the breathing 'in mind' while having many other wandering thoughts in their head at the same time.

P11: The more I stayed in the tent … the more I paid less attention to it and just 'was in the tent'. It was less about breathing but just being in the tent, you know, just relaxing […] I could afford to think about other things while still trying to breathe.
P20: I felt I had the breathing consistent inside the tent [so] my thoughts were jumping around and I didn't feel I had to focus on my breathing as much because it was sort of happening naturally. Outside of the tent I kept focusing back on the breathing, trying to get it consistent and my thoughts weren't so... I don't know, they were more just about t]he breathing, trying to stop it from jumping around.

For some of the participants the experience brought unexpected moments of clarity in thinking, or specific ways in which they could focus on their thinking. Some of our participants even explicitly said they thought of things that are usually very stressful for them, but they did not feel stressed at all at the time and there was often little attachment to the fleeting thoughts, letting them just glide by (as when falling asleep).

P25: Like, any worry just kind of floated away and issues you have become more clear, oh, that's what I need to do, I don't need to worry about that it's all fine. So … that kind of clarity.

P20: Interesting feeling to have stressful thoughts in your head and still feel relaxed. […] You can think about all these things without being anxious—feel a lot more focused on the stuff you have to do but without feeling stressed. It's quite hard to put into words.

P17: Is there a word to say 'easy to think'? […] Because it makes you relax so much so it is easier to think about stuff… or think about nothing rather than something specific, because I was still trying to concentrate on my breathing […] worries I had, I stopped thinking about them.

Participants also described a stronger feeling of connectedness to the tent and its movements when inside, while outside the link was less tangible. Some people specifically talked about how the movement in sync created a natural, harmonious space inside; but also how this connection made it more disruptive if the movements of ExoBuilding did not correspond to their breathing.

P22: Harmonises you to the environment, greater sense of harmony … [Inside it] creates [a] sort of unity with your environment.

P24: You can't escape the tent when you are inside it, it is easier to ignore when you are just watching it. [It felt] you're more ingrained, more part of it when you're inside. But also short movements [were] distracting inside [referring to movements out of sync with body] … more reason to bring it back under control …

P04: In the tent you are more integrated into the system, or you can feel it better what happens now, what your body will do.

P10: When I was inside and forgot to think about the breathing [so that the breathing started to be erratic], it 'slapped' me more … it felt much more 'gentle' outside.

4.2. Outside—non-immersive

Much of the above is very different for the non-immersive condition, when people were facing ExoBuilding from the outside, with all other experimental conditions left identical to the immersive condition. Very few people reported any specific relaxation experiences, most being very mundane. Only three people said they were more relaxed outside than inside. Two of those were part of the four participants who stated that they experienced issues with the mapping (see section below). The third stated that they disliked enclosed spaces in general. Roughly half the participants specifically stated that the non-immersive condition was unremarkable.

P25: Not sure, in a way you're just sitting and doing nothing.

P14: Normal, like siting in a sofa or whatever.

P17: Just sat on a chair and concentrated on my breathing.

Particularly, many seem to have perceived the tent as an external object that can be manipulated rather than the sense of connection described in the immersive condition. Many report that this outside perspective helped them sustain a more conscious focus on keeping attention to breathing, which the instructions specifically asked them to do.

P02: … being outside made me focus on the breathing a bit more because then it was like there's this object that I'm controlling... [while inside] is more massive, like if you're outside it is just an object, when you're inside its like you're in a room that is reacting to you, you're still like thinking about controlling it but not as much.

P11: I found myself really detached from the tent, so it was easy to sort of like look at and say right 'this is how I'm breathing'—you know I had that mental picture in my mind how that is taking place. And because of that it was a bit easier to sort of forget about other things and focus on the breathing.

P:25 I found it a bit easier to concentrate on breathing strangely, I don't know why, perhaps because I was able to see the whole thing, see it go up and down rather than towards me... but I felt not as super relaxed as when I was inside.

P19: Being outside it just seems you're watching it for one, but being inside you feel part of the tent, you feel more connected to the tent going up and down and moving around you. Whereas outside, you know you are controlling it, but... but you're not as connected as when you're inside, when it is all around you moving.

Many of these participants claim that concentrated focus on breathing was easier outside. This often meant that their thoughts did not wander in the same way as inside. When specifically asked about the differences between the immersive and the non-immersive condition, some participants highlighted this in a particularly poignant way.

P03: … forced outside, relaxed inside …

P25: … concentrating on the breathing [outside], rather than relaxing on it …

This does not mean that people never lost focus on the breathing instructions outside and got lost in their thoughts. However, the breathing instructions and having fleeting thoughts did not go together well outside, whereas the inside allowed *background* awareness of breathing freeing people up to concentrate on thoughts and to be more relaxed.

Please cite this article in press as: H. Schnädelbach, et al., The immersive effect of adaptive architecture, Pervasive and Mobile Computing (2014), http://dx.doi.org/10.1016/j.pmcj.2014.11.006

4.3. Behavioural changes beyond the instructions

As mentioned previously, mindfulness training directly inspired the specific breathing instructions. The aim was to draw on something established and tested, and something that would be applicable in the immersive and the non-immersive condition; we did not however frame the study as being about meditation in any way. For a considerable proportion of participants the specific instructions combined with the biofeedback driven environment led them to personal states that were deeply relaxed, and for some participants those states can be described as meditative.

Moreover, 3 participants (in our sample of 24) stated that they had previous experiences with meditation. Only one participant, P12, reflects on meditation in detail and it is worth considering some of their feedback for discussion. For P12, both the immersive and the non-immersive conditions allowed them to reach meditative states. Possibly this aspect of their response was mainly shaped by the instructions and the properties of the environment overall (darkened space, quiet environment, reclined seating position). The meditative states reached were markedly different however for the two conditions. They began by reflecting on meditation in general and how specific meditation techniques move you to a different state.

P12: Normal meditation practises usually take you out of . . . , what you think is real, they give you a higher perspective. And while being at a higher perspective you think of these physical changes very practically.

Reflecting on the immersive condition, they stated:

P12: When I was inside . . . , I was just concentrating on those lights coming near me and going away . . . It felt nice, it put me in a trance . . .

This triggered a reflection on the differences between immersive and non-immersive conditions:

P12: Maybe because of my position. I was just below that light [of the projection] and I had nowhere else to concentrate than that light. And while sitting outside my perspective . . . grew wide and I could see a lot of things and think.
P12: Yes, . . . it had a stronger effect on me. But I had more thoughts when I was outside but inside . . . —inside the atmosphere got a stronger hold of me and that's why I couldn't even think of other things than that light.
P12: The difference between these two were, ... When I was inside the tent I was getting high [in terms of perspective] and when I was outside I was having a practical approach on my real self.

In summary, it can be said that this particular participant, reflecting on his meditative practice, reported reaching a state similar to a trance when immersed, expanding their mind and seeing his physical location from above. When emerging from ExoBuilding, this allowed this participant to approach problems from a new perspective. In their view, it was essential that the reactive biofeedback link between themselves and ExoBuilding was present. During the non-immersive condition, this participant remained focused on practical thoughts and problems.

4.4. Implications of mapping issues

There were four people out of the 24 participants who specifically reported issues with the mapping between their respiration and the movement of ExoBuilding. In mapping participant respiration to the movement of the prototype, respiration is averaged to smooth the motion. Typically, when participants do not exhibit a relatively regular breathing pattern, this movement averaging can cause overcompensation by the mechanism. This was felt much more harshly inside compared to outside. Moreover, out of the four people who had strong problems with the tent not following their movements precisely, no one is in the group of 15 participants who reported strong experiences of relaxation, suggesting the high importance of a precise mapping of the movement to their own movements, which is akin to the discussion of 'breaks in presence' in the VR domain [21]. This is also supported by several people talking about how the movement in sync with breathing ''harmonises'' the environment.

5. Quantitative data

5.1. Questionnaire responses

The analysis of the questionnaires concentrated on the three core questions and the differences between responses on the 7-point Likert Scale between the two conditions. We compared the differences between responses to the three statements following each of the two experimental conditions with a one-sample t-test. There were no statistically significant differences.

5.2. Physiological data

No statistically significant differences were found between the immersive and the non-immersive condition. Paired samples t-tests were conducted for RSP-R, HR and HR-RSP-COH. The initial exploration of the descriptive statistics of the

Table 1
Descriptive statistics of physiological data for the two conditions. The recording unit is provided where appropriate. For each data stream, the number of valid data points (N), the Mean, standard deviation (Std. D), standard error of the mean (Std. E) and the P-value of the Shapiro Wilk test computed on the differences in the values are listed (SW Sig).

Condition	Im	N-Im		Im	N-Im
EDA	μS		HR	bpm	
N	24	24	N	23	23
Mean	27.6543	27.8023	Mean	68.9575	68.2728
Std. D	2.14450	2.45842	Std. D	10.92553	9.99794
Std. E	0.43774	0.50182	Std. E	2.27813	2.08471
SW Sig	0.000		SW Sig	0.316	
HR-RSP-COH	N/A		RSP-R	cpm	
N	23	23	N	24	24
Mean	0.3676	0.3592	Mean	14.2158	14.2113
Std. D	0.20425	0.23588	Std. D	2.82200	2.99144
Std. E	0.04259	0.04918	Std. E	0.57604	0.61063
SW Sig	0.109		SW Sig	0.990	

physiological data had highlighted non-normality only for the differences in EDA between inside and outside, following a Shapiro–Wilk test. The one extreme outlier identified in EDA difference was judged to be a permissible value. For EDA, where the differences in EDA were not distributed normally, a nonparametric-paired Wilcoxon test was conducted. Table 1 provides an overview of the descriptive statistics.

6. Discussion

We begin our discussion by summarising and interpreting our study findings, before presenting implications and plans for future work.

6.1. Differences in the experiences of the two conditions

Being aware of breathing came naturally to the majority of people in the immersive condition. It allowed people to *stay with their breathing* without consciously concentrating on it, enabled through a level of connectedness with ExoBuilding, while also being able to process other thoughts. One might compare this to Forlizzi's 'fluent interaction' [22], but also Wheeler's 'online intelligence', which describes our embodied–embedded way of interacting with the world [23]. Embodied behaviours such as riding a bicycle or navigating a familiar route come natural to us. We do not have to think about those, we just do them freeing us up to think about other things, and it seemed that ExoBuilding produced a similarly familiar relation between participant and environment in a rather short time frame. The group of participants who reported this relationship with ExoBuilding felt very relaxed, similar to just before falling asleep and this was enabled by a lack of distractions when being immersed by the actuated environment, resulting in a detachment from what was outside that environment. Finally, for some people the immersive effect provided for unusual levels of clarity allowing them to focus on their thoughts. The above results are in line with previous experimental work around ExoBuilding [16] and Sonic Cradle, a biofeedback driven sound scape [14].

In contrast, people saw ExoBuilding as an external object in the non-immersive condition, with much less of a felt connection to it. When outside, participants generally found it easier to focus on the instructions, which asked them to concentrate on their breathing. But, they had to consciously *concentrate* on their breathing to be able to stay with their breathing, despite the linked connection between their breath and the movement of the building. Any involuntary thoughts outside the concentration on breathing seemed to break that link. This in turn is very much comparable to Forlizzi's cognitive interaction [22] and to Wheeler's off-line intelligence [23]. The latter is very much focused on abstraction from our embodied–embedded interaction with our world. When we solve a maths problem, but also when we plan a route on map to navigate an unfamiliar area, we concentrate our cognitive effort on the particular task at hand. Participants reported requiring this effort when seated outside of ExoBuilding to stay with our respiration instructions. The non-immersive condition was then as described by most participants as less relaxing and a much more mundane experience.

6.2. Physiological data and questionnaire responses

The levels of activation, as expressed through EDA and HR did not differ between the conditions. Unexpectedly, respiratory behaviour, as expressed through RSP-R and RSP-HR-COH, did not differ significantly between conditions either, despite being achieved much more consciously in the non-immersive condition. However, the recorded respiration rates are within typical resting respiration rates and the coherence between respiration and heart rate is as high as previous comparable results [16]. We also did not find an effect of the conditions on the questionnaire responses, which were aiming at (self-reported) compliance with our instructions, where those simply asked participants to concentrate on their breathing and return to the concentration on breathing whenever their focus had lapsed. Self-reported adherence to the respiration instructions was therefore at the same level between the two conditions, and it seems that this was the overarching factor driving the physiological response of our participants. Our participants' ability to concentrate on their breathing was on average the same between the conditions. This resulted in similar respiratory behaviours, such as average respiration rates with an unremarkable level of coherence between Heart Rate and Respiration, where low and regular breathing triggers high coherence. Although we expected the immersive condition to offer better support to our participants with regard to adhering to our instructions, we did not find this being the case. However, the measured physiological data and the self-reported window into people's adherence to our instructions are entirely consistent with each other: participants did not report any differences in being able to follow our respiration instructions and, unsurprisingly with hindsight, they produced similar respiration behaviours.

6.3. Summary of study findings

Condition did not significantly affect actual physiological behaviour or compliance with our instructions. In this context, respiratory behaviour was shaped first and foremost by our experimental instructions. Our participants reported being able to follow our instructions in both conditions and produced very similar respiratory responses. However, *how* participants arrived at, and subjectively experienced, the exhibited physiological behaviours and *how* they reported complying with our instructions was markedly different as highlighted in the interview feedback. The work presented in this study has highlighted the experiential differences that are triggered by immersion in an exemplar adaptive environment in comparison to experiencing the same adaptivity as an external structure. Immersion clearly made all the difference to experience.

6.4. Implications and future work

Our study data, demonstrating how immersion impacts the experience of environments adapting to us, contribute to the understanding of our relationship with adaptive environments as they are becoming ever more widespread and expansive [24]. The immersion that ExoBuilding creates is very particular, as it results from a combination of digital technologies, an adaptive space and behaviours mediated by our instructions and previous experiences. This is a clear limitation of the presented study. However, even these initial results will begin to explain related work, mentioned throughout, emerging from interactive Arts, such as [6,7,25,26]. We also suggest that our results begin to highlight the potential advantages that presenting biofeedback in this immersive fashion has over more traditional presentations, through graphs on a screen [27,28], which is highly relevant for the growing area of pervasive healthcare [29]. Further study is required to compare those presentations with each other.

As already argued in the introduction, the research field of Adaptive Architecture looks to the potential of environmental adaptivity more broadly considering inhabitation as a key concern. Experimental work continues to push the boundaries of what is feasible and practical [30]. This type of experimentation has the habit of influencing mainstream architecture over the medium to long term, as for example seen in high-tech architecture emerging from Archigram's earlier experimental work [31]. However, the experimental explorations are not systematically studied to allow fundamental understandings to influence building practice. The resulting successes and failures of the translation of this experimentation into our built environment affects us all. In future, Adaptive Architecture more generally might be reactive to personal data streams in many different ways, for example reacting to locative information, social networking data or to direct interactions and this application of personal data in the built environment is currently growing. We envisage that some of this data will be used to generate interactive couplings between environment and inhabitants in a similar way to that explored here. In future work, we endeavour to explore this with many different data streams, with multiple participants and with different mappings to understand how being immersed in personal data will affect us, and therefore how to best support the design of the buildings around us. We are also keen to expand our work with stakeholder groups who have an inherent interest in respiration and might benefit from it being embedded in the environment. For this reason, we are in the process of conducting in-depth research with practitioner's of yoga where an awareness of breathing is essential to the practice, a first documentation of this work being available here [32]. This is on-going and we are exploring how groups of yoga teachers and students can make use of ExoBuilding for different parts of their practice.

Acknowledgements

We would like to thank all participants in our study, the internal and external reviewers of our research and the UK EPSRC, who funded this research through grant EP/F03038X/1.

References

[1] S. Brand, How Buildings Learn: What Happens After They're Built, Viking, London, UK, New York, USA, 1994.
[2] H. Schnädelbach, Adaptive architecture—a conceptual framework, in: Proceedings of MediaCity2010, Bauhaus-Universität: Weimar, Germany.

ARTICLE IN PRESS

[3] M.C. Mozer, Lessons from an adaptive house, in: D. Cook, R. Das (Eds.), Smart Environments, Technologies, Protocols and Applications, Wiley & Sons, Hoboken, USA, 2005, pp. 273–294.
[4] M. Gillott, Creative Energy Homes. 2010. Available from: http://www.nottingham.ac.uk/creative-energy-homes/creative-energy-homes.aspx [cited 11.09.13].
[5] D.J. Cook, J.C. Augusto, V.R. Jakkula, Ambient intelligence: technologies, applications, and opportunities, Pervasive Mob. Comput. 5 (4) (2009) 277–298.
[6] M. Jacobs, J. Findley, Breathe. 2001. Available from: http://www.fundacion.telefonica.com/es/at/vida/vida10/paginas/v4/ebreathe.html [cited 2013 29/01/2014].
[7] G. Khut, J. Tonkin, Drawing Breath, 2005–2006. 2005. Available from: http://georgekhut.com/2005/09/drawing-breath/ [cited 04.02.11].
[8] O. Khan, Open columns | A CO_2 actuated responsive architecture. 2011. Available from: http://cva.ap.buffalo.edu/opencolumns/?page_id=31 [cited 10.02.11].
[9] H. Schnädelbach, K. Glover, A. Irune, ExoBuilding—breathing life into architecture, in: Proceedings of NordiCHI2010, ACM Press, Reykjavik, Iceland, 2010, pp. 442–451.
[10] M.A. Fox, M. Kemp, Interactive Architecture, Princeton Architectural Press, New York, 2009.
[11] B. Sheil, Protoarchitecture: Analogue and Digital Hybrids, Architectural Design, John Wiley, London, 2008.
[12] P. Beesley, O. Khan, Responsive Architecture/Performing Instruments, in: Situated Technologies Pamphlets, vol. 2(4), 2009.
[13] L. Bullivant (Ed.), 4dspace: Interactive Architecture, Architectural Design, Wiley-Academy, 2005.
[14] J. Vidyarthi, B.E. Riecke, Mediated meditation: cultivating mindfulness with sonic cradle, in: CHI'13 Extended Abstracts on Human Factors in Computing Systems, ACM, Paris, France, 2013, pp. 2305–2314.
[15] M. Chan, et al., A review of smart homes—present state and future challenges, Comput. Methods Programs Biomed. 91 (1) (2008) 55–81.
[16] H. Schnädelbach, et al., ExoBuilding: physiologically driven adaptive architecture, ACM Trans. Comput.–Hum. Interact. (TOCHI) 19 (4) (2012) 1–22.
[17] P.M. Lehrer, E. Vaschillo, B. Vaschillo, Resonant frequency biofeedback training to increase cardiac variability: rationale and manual for training, Appl. Psychophys. Biof. 25 (3) (2000) 177–191.
[18] Mind Media B.V. Mind Media B.V. Information about the Nexus-10. 2010. Available from: http://www.mindmedia.nl/english/nexus10.php [cited 09.02.10].
[19] P. Grossman, et al., Mindfulness-based stress reduction and health benefits: a meta-analysis, J. Psychosom. Res. 57 (1) (2004) 35–43.
[20] J.T. Cacioppo, L.G. Tassinary, G.G. Berntson (Eds.), Handbook of Psychophysiology, third ed., Cambridge University Press, Cambridge, UK, 2007.
[21] M. Slater, A. Steed, A virtual presence counter, Presence: Teleoper. Virtual Environ. 9 (5) (2000) 413–434.
[22] J. Forlizzi, K. Battarbee, Understanding experience in interactive systems, in: Proceedings of the 5th Conference on Designing Interactive Systems: Processes, Practices, Methods, and Techniques, ACM, Cambridge, MA, USA, 2004, pp. 261–268.
[23] M. Wheeler, Reconstructing the Cognitive World, MIT Press, Cambridge, USA, 2005.
[24] D.J. Cook, S.K. Das, Pervasive computing at scale: transforming the state of the art, Pervasive Mob. Comput. 8 (1) (2012) 22–35.
[25] L.C. Guerra, T. Todoroff, Y. Sebti, Lungs The Breather. 2008. Available from: http://www.thebreather.org/ [cited 04.02.11].
[26] J. Vidyarthi, B.E. Riecke, D. Gromala, Sonic Cradle: designing for an immersive experience of meditation by connecting respiration to music, in: Proceedings of Designing Interactive Systems, ACM, Newcastle Upon Tyne, UK, 2012, pp. 408–417.
[27] Western Cape Direct LLC. Stresseraser. 2010. Available from: http://stresseraser.com/ [cited 09.02.10].
[28] Mind Media B.V. Mind Media B.V. Information about BioTrace+ Software. 2010. Available from: http://www.mindmedia.nl/english/biotrace.php [cited 09.02.10].
[29] F. Delmastro, et al., Special issue on pervasive healthcare, Pervasive Mob. Comput. 8 (6) (2012) 811–812.
[30] S. Bonnemaison, R. Eisenbach, Installations by Architects: Experiments in Building and Design, Princeton Architectural Press, New York, 2009.
[31] P. Cook, Experimental Architecture, Universe Books, New York, 1970.
[32] N. Jäger, S. Moran, H. Schnädelbach, Using adaptive architecture to support Yoga practices: social considerations for design, in: Proceedings of 2014 IEEE International Conference on Pervasive Computing and Communications Workshops, PERCOM Workshops, 2014.

Please cite this article in press as: H. Schnädelbach, et al., The immersive effect of adaptive architecture, Pervasive and Mobile Computing (2014), http://dx.doi.org/10.1016/j.pmcj.2014.11.006